DEVELOPMENT OF BIODEGRADABLE TEXTILE COMPOSITE MATERIALS BY USING NATURAL FIBRES AND WASTE TEXTILES

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ABSTRACT

The development of biodegradable textile composite materials by using natural fibres and waste textiles. NUMTISS project aims to develop a modelling approach of the exact geometry of 3D fabrics taking into account both parameters of the weaving process until those of the resin infusion. Classification and fabrication method of 3D woven textiles and information for both the textile and composite engineers in developing textile composites for advanced applications like civil airplanes are focused. A unit cell generating method for technical reinforcement textiles was introduced. And application of digital elements for the simulation of the mechanical behaviour of textile reinforcement structures by means of a finite element analysis is studied. The relationship between fibre geometry and the damage sequence under tensile loading has been investigated for a composite material reinforced with different textiles architectures such as mat and woven. This paper also focuses observe, analyse and identify the process and progress of the generated damage and the failure mechanism which leads to the materials fracture.

Keyword : *3D woven textiles, unit cell, textile composites, fabric modelling, NUMTISS*

INTRODUCTION

Textiles are found to be among the most efficient reinforcements for composite materials, using textiles, the employment of fibres such as carbon, glass, etc., and has been augmented in several industrial applications. These composite materials allow the manufacture of complex shapes in a single operation or process. Recent advances in textile manufacturing process and resin transfer molding techniques have led to the development of what are known as textile structural composites. Textile composites are the promising new class of composites finding their applications in aerospace, automotive and manufacturing industries as they posses exceptionally high ratios of strain to failure in tension, compression or impact load as compared to traditional unidirectional pre-preg composites. All of these factors can affect the deformation behaviour during forming leading to variations in the formed fibre pattern, we focus on prediction of the effects of process boundary conditions, blank size and forming temperature on the forming quality of a hemisphere using a rate/temperature-dependent hybrid FE model. Many of 3D structures can be made on the conventional weaving machines with less or no modification. The main advantage of these 3D structures is that they give structural integrity of the woven structure, the satisfaction of the geometric shapes, and volumes that are used in many end-use applications. The properties and geometry of textiles mainly depend on yarn construction and process parameters. Representative Unit cells are used for structural and mechanical analysis of textiles. Numerical drape simulations have increasingly been used in the last decade to predict the ability of textiles to form a complex three-dimensional shape. Traditional RUCs are built by mathematical assumptions which gives a result based on the assumption than realistic images of unit cell geometry. Construction of several RUCs composed of digital elements is focused in this paper. The geometric modelling of the unit cell is done using open source codes TexGen developed at University of Nottingham (U.K.). The development of high-performance composites made from natural resources is increasing worldwide day by day. In this sense, the use of natural fibres for technical composite applications has recently been the subject of intensive research and many studies have previously focused on natural fibres as potential reinforcements in composites. The development of natural fibre composites is limited. Textiles find their applications as reinforcement in composites. Textile materials can also have three–dimensional architectures and the production of some of the most complex fittings eliminates the intermediate stages of preforms and the possibility of controlling the final shape from the material design stage. Indeed some numerical model exists for the braiding process and the knitting process, but not yet for the weaving process.

METHODOLOGY

MATERIALS

Plain woven fabric and Leno woven fabrics was used for modelling of textile composites because they differ in yarn construction but composed of technical E-glass multifilament yarns.

1. Plain woven fabric - yarn cross each other at every point of intersection

2. Leno woven fabric – yarns are straight aligned but bound together by a binding warp yarn.

Composite materials studied were manufactured using epoxy resin as a matrix reinforced with textiles made up of glass fibre. Woven textile constituted of glass fibre type E of 0.4 N/tex, which is identified by its two main directions (length and width) as it is woven it is typified as a biaxial fabric.

The materials used were 1 · 4 satin weave, and 4 · 4 twill weave, carbon/epoxy pre-preg manufactured by Hexcel Composites. Fibre volume fraction is 49% for both materials prior to consolidation. The yarns in the present analysis are considered as an orthotropic- solid bodies, whose longitudinal direction which is parallel to fibre is defined by 11 and transverse plane is designated by the directions 22 and 33 respectively, while the Poly Phenylene Sulfide (PPS) matrix in the modelling scheme is assumed to be isotropic. Mechanical behaviour of unit cell is predicted by incorporating a transversely isotropic material law.

PREDICTIVE MODELLING FOR OPTIMIZATION OF TEXTILE COMPOSITES

Wrinkling mechanisms: The significantly large differences in the stiffness of fibres and the polymer matrix results in two possible ways in which wrinkling could occur during textile composite forming. From the view point of micro/meso-scale deformation, several researchers including Long et al. identified in plane and inter-ply shear as the important mechanisms governing forming of aligned fibre composites. The formed fibre pattern is governed mainly by the trellis effect, i.e., local intra-ply shearing between initially orthogonal fibres. The force (compressive stress) causing buckling comprises two main components: membrane force and loading force due to contact with tools. Wrinkles should be homogeneous in the circumferential direction for an isotropic material. It is of crucial importance to understand that the material responds differently to boundary conditions for the two wrinkling mechanisms. For the first case, the change in tow architecture during deformation depends strongly on the in-plane tension in the material, which can be controlled using a pressure blank-holder. For the second case, the viscoelastic shell wrinkling behaviour is a result of geometry, material stiffness and, more importantly, in-plane loading distribution across the edges of the blank. Similarly, both wrinkling mechanisms are significantly influenced by forming temperature.

Boundary conditions: Isotropic holding force (75 N), equal tensile stresses generated in both bias directions, i.e. at ± 45 degree to the warp and weft directions and equal tensile stresses generated along both tow directions, equal tensile stresses generated between two directions (warp and weft) but using alternative pad locations, unequal tension generated along bias directions using two diagonally opposite pads.

FE simulation: In this study, numerical simulations of the forming of a viscous textile composite over the hemisphere were conducted using a rate/temperature-dependent hybrid FE model in a commercial Finite Element (FE) code.

Multi-scale energy model: The MSEM predicts the constitutive behaviour of viscous textile composites by considering the behaviour of constituent components. The modelling approach involves a summation of energies dissipated during shearing of a textile composite comprised of two initially perpendicular groups of uniaxial fibre tows, by relating the properties to the rheological behaviour of material constituents, thus allowing the shear behaviour to be predicted at any rate and temperature.

Non-orthogonal constitutive model: The role of the NOCM is to model the stress–strain relationship dependent on the fibre directional properties, i.e., the fibre directions are tracked, ensuring that non-orthogonal material axes are updated as the simulation of progress. The model was developed in an explicit mathematical form using a homogenization method. Hemisphere forming simulations Hemisphere forming simulations were conducted using the model illustrated. 1859 linear truss elements and 900 quadrilateral membrane elements were used to model the standard blank (300 · 300 mm). The mesh orientations of the blank align with the fibre directions. The die and punch were meshed with 4-noded bilinear quadrilateral rigid elements. Eight node sets were generated to represent the eight pressure pads. Realistic experimental boundary conditions such as forming rate and temperature were used, and tool-ply friction was also incorporated in the simulation.

Figure 1: Predictive Modelling

Experimental set-up for hemisphere forming with segmented blank-holder

NUMERICAL MODELLING OF TEXTILE COMPOSITES

Three different natural fibres were investigated in the present study: flax, jute and hemp. The flax and jute fabrics were commercially produced for fibre resin composite fabrications. Natural fibres have complicated structures in microscopic view. The major constituents of natural fibres are cellulose, hemicellulose, lignin, pectin and ash. The amount of these components affects directly the properties of the fibre, since the hemicellulose is responsible for the moisture absorption, bio and thermal degradation whereas lignin ensures thermal stability but is responsible for the UV degradation. Unsurprisingly, significant variations are observed, obviously connected to biological differences among plants, climatic history, geographic area, type of cultivation and fibre extraction technology. Tensile modulus of natural fibre reinforced composites would be higher when all microfibrils are aligned along the fibre's direction, where tensile loading is applied. The internal structure of natural fibres is contingent upon the age and origin of the plants and climate conditions. Moreover, microfibrils are not identical as they are comprised of crystalline and amorphous regions.

Experiments on fibre resin composite plates: Composite textiles with reinforcement materials comprise a wide range of reinforcement material in the form of textile preforms which may be constituted by non–woven, woven or knitted materials. In order to select the optimal technology for preparing textile preforms, it is necessary to consider both the strengths and weaknesses of each technology. Different methods are used to obtain composite structures: Embedding the reinforcement material (woven textile) into a resin matrix. The simplified lay–up process. The 0/900 plain weave fabric layers. From the point of view of process–ability, the polyester resin is easier to use due to higher viscosity and low density. The hardener acts quickly and is highly concentrated, so a 2% addition is sufficient in most cases. The addition of hardener depends on the amount of base that is prepared at a single casting. Curing of warp yarns on the weaving loom: E-glass warp yarns have been cured with tensile on an industrial weaving loom to get the exact cross section of warp yarn when we produce a fabric and it is circular, since the initial roving which has a quasi-rectangular cross section has been twisted to 25 twists/metre to reduce damages due to the yarn friction.

Numerical model (FEM): For the numerical modelling of the weaving process using finite element method, we considered all elements like rigid solid, and we assume that yarns can be considered as transverse isotropic elastic materials. For modelling, at least three warp yarns and four weft yarns have been represented. High speed camera results achieved previously on a loom have highlighted that the influence zone of reed compaction spreads over 4 weft yarns. Yarns setting up: Yarns were modelled with a transverse isotropic elastic law. For meshing parts, 8-nodes hexahedra solid elements were used. Existing and checked material law of para-aramid yarn was first used, but will be replaced later by E-Glass material law after several mechanical experiments.

Reed setting up: Reed was modelled by a steel plate composed of 4 quadrilateral elements, in which horizontal displacement has been imposed.

Boundary conditions: Warp yarns displacement is set by the simulation of heddles vertical motion. Weft yarns are constrained to a free horizontal motion. Weft yarns tension that occurred during weaving is modelled by fixing weft yarns at edges. The warp and weft interlacing yarns zone is modelled by a rigid plate that can stop weft yarn when the reed is beating. Kinematic simulation on weaving loom: Since the model is computed using explicit schema with finite element code Radioss, it was decided to perform an acceleration of the weaving kinematic for decreasing computation time. The weaving cycle which lasts 600 ms for a weaving speed of 100 RPM, was accelerated to 1.6 ms for our model.

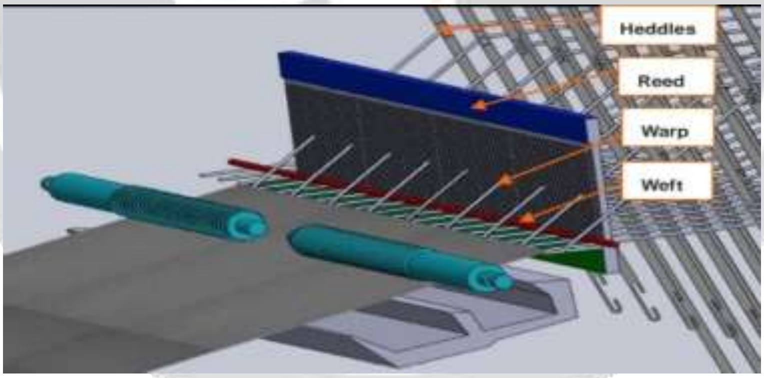

Figure 2: Geometric Modelling

UNIT CELL GEOMETRY

The unit cell which is an essential component of textile modelling is modelled using TexGen with the assumption that both the warp and weft yarns possess similar geometric and material properties. The schematic for 5-Harness satin weave unit cell generated by TexGen. The dimensions (length (l) x width (w) x depth (t)) of the unit cell and the set of input data used in geometric modelling.

Finite Element Modelling:

The geometric model of unit cell which is created using TexGen is further transferred to ABAQUS through python script for FE analysis. For this purpose TexGen and ABAQUS are used in combination because of their similarity in Python scripting interfaces as the codes required for linking the above two were written by the researchers of University of Nottingham. Issues related to FE modelling such as contact between the yarns, creation, submission and detailed analysis of the job are taken care of by the fully automated python script which contains the code that creates the TexGen model while the outer surfaces of the yarns are defined when the program loops over the hierarchy of textile. Three-dimension 8 nodded brick element with reduced integration (C3D8R) were found to be the most applicable element for these analyses as brick elements have the ability to incorporate mid- side nodes (producing 21-node elements) and several material models.

A procedure for determining the three-dimensional elastic constants from the unit cell analysis is described. This method is used to determine the shear modulus G., and the results compared with the transverse shear stiffness of a thin textile beam. The unit-cell analysis assumes that the material is subjected to a uniform state of strain in a macroscopic sense. The average stresses required to create such a state of strain is computed from the finite element model of the unit cell. In the microscale all unit cells have identical displacement, strain and stress fields. Continuity of stresses across a unit cell then requires that tractions be equal and opposite at corresponding points on opposite faces of the unit cell (periodic boundary conditions). Since the displacement gradients are constant for a homogeneous deformation, the displacements at corresponding points on opposite faces of the unit cell differ only by a constant.

Techniques for generating Unit Cell

1. Mathematical approach: Trace of yarn was determined by mathematical functions using equations which are used for geometrical description of a plain woven unit cell.

2. Microscopic and microtome optical analyses: The method of a microtome sectioning analysis was described by Rief et al. And Hivet and Boisse introduced microscopic analysis method. The main advantage of this approach is that the dimensions and the geometry are reproduced directly from the actual textile, which gives an accurate result accurate. The disadvantage is that there is the need for a Sample of the examined material.

3. Generating unit cells of textile structures: A method to compound a woven Unit cell out of micro- and macro-blocks was introduced by Tan et al. Wang et al. presented an approach in which digital elements were used. A non-continuum approach was also found, which enabled a “near filament-level resolution”.

Novel method for generating Unit Cell on a solution near Microscale Solution

The main aim of the introduced method is to achieve a proper yarn configuration that equates the one of the examined textile in its static equilibrium. The behaviour of digital elements was analysed. The yarn is straight and stress less in the beginning of the simulation. By the prescribed motions, the aligned yarn segments are forced to come up with the textiles’ yarn construction. The unit cell borders were defined and they correspond to the warp and weft densities which were determined by optical analysis. The yarn crimp was also considered. Finally, the boundaries of prescribed motion were disabled and then reduced to a minimum required for determining the symmetry.

Figure 3: Steps of Plain Woven fabric Unit Cell generation process

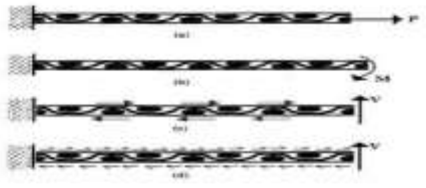

Figure 4: Geometry of Unit Cell

3D WOVEN TEXTILE PERFORMS FOR COMPOSITES

The comparison and classification of textile preforms is a difficult task due to availability of many forms of 3D fabrics.

1. Three-dimensional solid woven preforms

3D solid woven fabrics are manufactured by incorporating and manipulating yarns in the length, width, and the through-the-thickness directions. The through-the-thickness yarn is incorporated at varying levels and angles in order to obtain the desired mechanical properties.

- Orthogonal woven architecture: Orthogonal structures are a 3D structure which contains straight yarns in the three principal directions that providing a stiffer and stronger preform against tensile loading.

- Angle-interlock woven architecture: Angle-interlock structures have a set of straight weft yarns and a set of warp yarns that weave with the weft in a diagonal direction in the thickness.

- Multilayer woven architecture: They have clear definition of fabric layers in the thickness of fibre. Each layer is composed of a set of warp ends and a set of weft yarns and layers are connected together through weaving.

2. Three-dimensional hollow woven preforms

3D hollow woven preforms can be generally divided into two types which can be manufactured by conventional weaving technology.

- Hollow fabrics with flat surfaces: This type of hollow fabric incorporates three or more layers of fabric. In the case where three layers of fabric are used, the layer of fabric connecting the top and bottom layers will be woven and the length of middle layer is found by fabric thickness. 3D hollow structure with flat surfaces was invented by Rheaume. Chen and Wang modeled the mathematically hollow fabrics with flat surface along with algorithms for design and manufacture of fabric. ‘Spacer fabric’ is a similar type of fabric which is composed of two parallel layers of fabrics connected by vertical yarns/fibres.

- Hollow fabrics with uneven surfaces: Takenaka and Eiji, based on the multilayer principle fabricated a 3D hollow fabric. The adjacent layers of fabrics are combined and separated at arranged intervals. Chen et al. studied the mathematical modeLling of this structure and an algorithm was created for the computerized design and manufacture of this type of hollow fabric.

3. Three-dimensional shell woven fabrics

Fabrics that form doubly curved shell structures where fibre continuity is maintained are called 3D shell woven fabrics. They can be made using different techniques.

- Weaving with discrete take-up: Busgen invented a method for the creation of 3D shell fabrics by direct weaving. In a conventional loom, take-up and let-off mechanism were modified for this process. Chen and Tayyar added an easy-to-use add-on device to the conventional loom for making 3D shell fabrics.

- Use of combined weaves: When weaves with different float lengths are used, the flatness of the fabric will be affected. The fabric section made from short-float weave will tend to expand, whereas the fabric section made from long float weave will tend to shrink which leads to bubbled effect of fabric. The same principle is used to create 3D shell woven fabrics.

- Shell fabrics by molding: Due to the extensibility and the allowance of shear in yarn /fabric, most flat woven fabrics can be molded into doubly curved surfaces to some extent. This extent is quite limited, mainly due to the friction between the warp and weft yarns at cross-over points.

- Use of origami principle for box shells: Shell shapes may also be in the form of an open box. Chen and Tsai proposed that the origami (paper folding) principle can be used to fold the box shell. There are usually different ways to get it folded in such a way that is suitable for weaving for a given box shape that is to be woven. The optimal solution used for folding must give the best fibre orientation.

4. Three-dimensional nodal woven fabrics

A 3D nodal fabric refers to a fabric which facilitates a network formed by different tubular or solid members joining together. Woven nodal structures from the plain weave using thermal reactive fibres, nodal structures based on the use of a jacquard loom and tubular members within a 3D fabric were developed. One important issue in manufacturing nodal fabrics is the smooth intersection of two tubes with or without the same diameter which resulted in the development of computerized algorithms.

5. Three-dimensional woven architectures from specially made devices

The creation of 3D fabrics are limited because conventional weaving machine allows the weft yarns to be inserted only in one direction. A 3D textile assembly using a purpose-made weaving device from static yarns oriented in the Z direction was developed. Based on the orthogonal structure, a method for creating variable cross-sectional shaped 3D fabrics was realized. Based on the belief that weaving must involve yarns interlacing with one another, weaving machine with dual-directional shedding operation was developed.

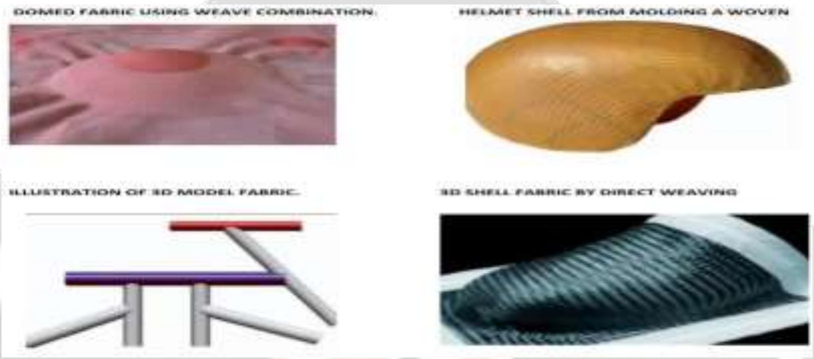

Figure 5: 3D Woven Textiles

CONCLUSION

Textile technology is the only approach that can organize unidirectional materials into 2D and 3D assemblies with desired shape, dimension, and to some extent material orientation. This paper reviewed the 3D woven fabrics in the different categories, unit cell, numerical and predictive modelling of textile composites. The manufacture and mechanical characterization of textile reinforced composites made up of mat and woven fabrics employing epoxy resin as a matrix were achieved. The reinforced composite presented sudden and catastrophic fracture when the first significant sign of damage appeared, without exhibiting a previous progressive failure along the sample; such behaviour was due to the random orientation of the continuous fibres. The unit cell of a textile composite beam was analysed to determine the flexural stiffness properties. The unit cell was modelled using eight -node plane strain finite elements. Unit cell analysis of 5-Harness satin weave fabric composite is performed and the results are compared and found to be in reasonably good agreement with the experimental data and theoretical model for the similar material available in the open literature. The developed model also facilitates the scope for altering the weave pattern and yarn parameters such as yarn spacing, yarns width, fabric thickness and different material properties for the warp and fill yarns. A numerical model was performed to describe strain phenomena of yarns when we produce plain weave, 2-2 twill and satin 8 fabrics. Good stiffness coefficients, good friction coefficients and a "transverse" behaviour's law will be implemented. The significant challenge for producers and supplier to handle with natural fibre reinforced polymer composites resides in large inconsistency of their properties. The chemical composition of vegetal fibres relies on several factors comprising fibre variety, time of harvesting, climatic history, soil characteristics and fibre processing technology. All these factors exert an influence on their final properties when used as reinforcements in bio composite materials. The results from the experiments and the simulations both show that the stress fields in the material and the tow patterns are very sensitive to holding pressure distributions, blank size and forming temperature as expected .The study has revealed that wrinkling is a result of the interaction between shear deformation and compressive force. Digital elements are suitable for modelling technical multifilament yarns. Textile models are useful for analysing textiles' geometrical structure when composed out of digital multi-element chains. The analysis of the mechanical behaviour with the use of the digital elements is still outstanding.

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